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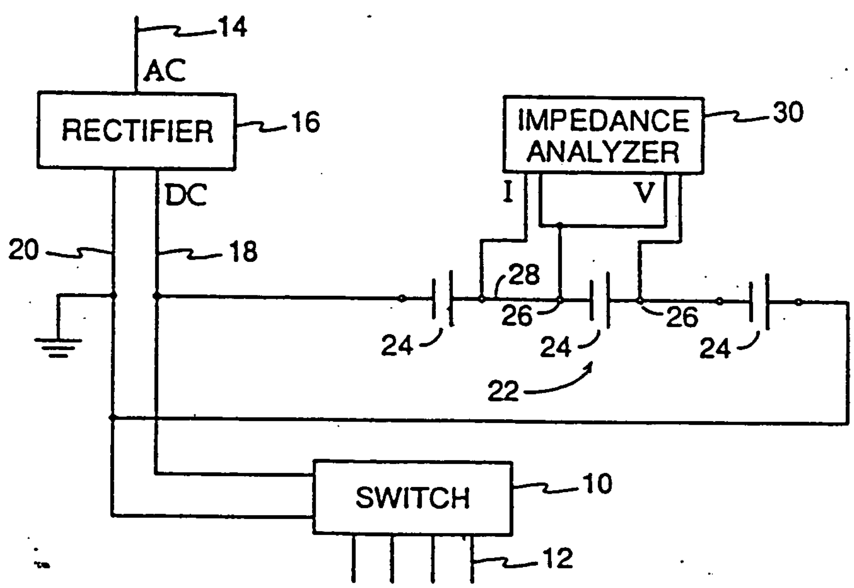
(54) Title: TESTING A BATTERY CONNECTED TO OPERATING EQUIPMENT



(57) Abstract

A method and apparatus for testing a string of batteries (24) connected to a power supply (18) for operating electrical equipment (10). The equipment inherently provides a source of broad-band noise. Current is measured across a conductive link (28) which interconnects adjacent batteries. Voltage across a selected battery is also measured. An impedance analyzer (30) combines the measured current and voltage to determine the impedance over many sampling periods. This data is Fourier transformed to obtain the frequency-dependent complex impedance of the selected battery, which can be related to the selected battery's capacity.

Testing a Battery Connected to Operating Equipment

SPECIFICATION

Field of the Invention

The invention relates generally to batteries. In particular, the invention relates to electrically characterizing batteries.

Background Art

Many types of electronic equipment must operate with high reliability and minimal service outages, even of short duration. For example, the telephone network is designed to operate even if the local power supply is interrupted, as is likely to occur during hurricanes, ice storms, and the like. A common practice is to use backup batteries, as illustrated for a telephone switching office in FIG. 1. A modern telephone switch 10 is a computer-based system which switches messages between multiple lines 12. Some of the lines 12 may extend directly to telephones in the home or office, in which case the switch 10 and its peripheral equipment supplies all required power to the telephones. Other lines 12 extending between switching offices or to remote sites are multiplexed. Because the switch 10 is based on a computer, it is important that even momentary interruptions of its power be avoided since restarting the computer may require hours.

The local power company delivers primary power to the switching office over a commercial AC power line 14, which may be multi-phase and at moderately high voltages in view of the large power required. A rectifier 16 converts the primary power to DC power on a DC power bus 18, a typical voltage in the telephone industry being –48 VDC with respect to a ground bus 20. The switch 10 and its computer are designed to operate with this DC voltage. One or more battery strings 22 of cells 24 are continuously connected to the DC bus 18. That is, the DC bus 18 floats on charged cells 24 and acts to keep them charged. Twenty-four lead-acid electrolytic cells 24 in the battery string 22 produce the desired 48 VDC. If the AC power is for any reason interrupted, the battery string 22 provides immediate backup power until AC power is restored or until a local diesel-powered electrical backup generator is started. This figure does not illustrate several elements of an operating power system, but these are well known in the telephone industry.

The lead-acid batteries present one feature of the switching office which has not changed over many decades. Although they are considered to be highly reliable, they nonetheless have finite but somewhat unpredictable lifetimes. Their capacity, that is, the amount of charge they can deliver, decreases as they age. They are replaced on a set change-out period, but economics dictate that this period be as long as possible, on the order of decades. It is preferable to test the batteries' capacity during this long service life to detect any failing or weak batteries.

The typical method of testing a battery's capacity is to charge it up, then completely discharge it across a load, and measure the total charge delivered to the load. Thereafter, if the battery passes the test, it is recharged and put back into service. Such a method, however, requires that the string of batteries be removed from service during testing. This method thus compromises the backup power during testing or requires alternate backup. Furthermore, it is a long procedure consuming much power.

It has recently been recognized that battery life can be correlated to the impedance of the battery cell measured at one or more frequencies. Because the impedance is measured at a finite frequency, the voltage inputs of an impedance meter 26 can be connected across one of the cells 24 left connected within the string 22 and with the string 22 connected to the DC bus 18. That is, the measurement is performed *in situ*. An oscillator 28 controls a current amplifier 30 connected in series with the string 22 and also provides an AC signal to the current input of the impedance meter 26. The impedance meter 26, which may simply be a phase-sensitive detector, measures the complex impedance of the battery under test. If the frequency of the oscillator 28 is variable, the impedance meter 26 can be used to produce a Nyquist plot, which is the locus of the real and imaginary parts of the complex impedance determined by the ratio of the measured voltage and current as the frequency of the test signal is being varied. DeBardelaben discloses in "Determining the end of battery life," *Proceedings of the Intelec Conference in Toronto,"* 1986, pp. 365-368 a method of measuring cell resistance at 5 *Hz* and correlating that resistance to cell capacity. Hampson *et al.* discloses a more elaborate approach in "The impedance of electrical storage cells," *Journal of Applied Electrochemistry*, volume 10, 1980, pp. 3-11 in which the measured Nyquist plot determines electrical component values of an equivalent circuit of the battery. Electrical values of the components can be directly related to aging or capacity.

However, this method is not fully satisfactory when performed *in situ* with an operating switch 10, which produces a substantial amount of noise on the DC bus 18 due to its switching operations. If the impedance test signal has a low amplitude, the noise will overwhelm the measurement. If, on the other hand, the

impedance test signal has a large amplitude, the test signal may cause errors in the switch 10. Boksiner *et al.* has disclosed in U.S. Patent 5,047,724 a method of detecting arcing from the DC power bus in which they measured both the current and voltage power spectrum of noise on the bus. However, this method cannot be used to characterize the batteries.

Summary of the Invention

The invention may be summarized as the method and apparatus for *in situ* testing of batteries connected across a DC power bus connected to an operating piece of electronic equipment. An analyzer determines the electrical characteristics of a battery by measuring an electrical signal produced on the battery by the noise signal imposed either by the power supply or the equipment itself. For example, the analyzer may use a Fourier transform to determine the frequency dependence of the measured complex impedance and thereby produce a Nyquist plot resulting from the system-impressed noise.

Brief Description of the Drawings

FIG. 1 is a schematic diagram of a prior-art method of measuring the capacity of a battery.

FIG. 2 is a schematic diagram of the method and apparatus of one embodiment of the invention for electrically characterizing a battery.

FIG. 3 is a Nyquist plot of data taken according to the invention.

Detailed Description of the Preferred Embodiment

The invention utilizes the fact that the noise inherent in an operating electronic system and its power supply can be directly used as the test signal for characterizing the backup battery system. A substantial portion of the noise in a switch 10 is random due to the statistical nature of telephone traffic. Hence, at least a portion of the noise is white noise.

An embodiment of the invention is illustrated in the schematic diagram of FIG. 2. Each cell 24 has two electrode terminals 26, and two neighboring battery cells 24 are electrically connected with a conductive link 28. The two voltage inputs of an impedance analyzer 30 are connected across terminals of the cell 24 under test. Although there are several ways to measure current including current loops, the finite resistance of the link 28 can be exploited by connecting the two current inputs of the impedance analyzer 30 across one of the links 28. These current inputs in fact measure a voltage which is assumed to be proportional to current. Extraneous noise is reduced by connecting the grounded side of both the voltage and current inputs to a single terminal 26.

The impedance analyzer 30 repetitively samples both the current and voltage signal during short sampling periods extending over a long recording period. At the end of the recording period, it Fourier transforms the data to provide the frequency distribution of both signals. These distributions can be used to generate the frequency distribution of the noise power. The complex ratios of the frequency-dependent current and voltage values provide the frequency-dependent complex impedance of the battery 24 under test. The impedances can then be used to generate a Nyquist plot, and thereby use the model formalism of Hampson *et al.* to characterize the capacity of the battery cells 24.

By means of the invention, each battery cell 24 can be separately characterized without disconnecting it from the string 22. Of course, more than one battery cell 24 could be simultaneously tested to determine if any of those cells 24 exhibit excessive aging.

Example

The invention was used to test a string of sealed lead-acid batteries backing up an operating Northern Telecom DMS—100 digital switch. The impedance analyzer was a dynamic signal analyzer, Hewlett—Packard Model 3562a. The AC signal amplitude across each set of leads was several millivolts, but the cell voltage of 2 *VDC* produced a comparatively large DC signal. Accordingly, both the current and voltage signals were AC coupled into the analyzer with a low-frequency cutoff of 3 *Hz* although useful signals were obtained down to 100 *mHz*. The frequency range of the measurements extended from 0.125 to 1000 *Hz*.

The envelope of the noise power distribution showed a fairly white distribution. However, the low-frequency noise distribution was resolvable into peaks at 6.75 *Hz* and 20 *Hz* and their harmonics. The 20 *Hz* noise can be associated with the frequency used for telephone ringing excitation, but the 6.75 *Hz* noise appears to be characteristic of the type of switch. Furthermore, there were strong harmonics of 60 *Hz* from the AC power.

The impedances for two batteries were converted to Nyquist plots, one of which is shown in FIG. 3, with the link resistance estimated to be 50 $\mu\Omega$. In both cases, for frequencies above about 40 *Hz*, the Nyquist plot linearly approached the origin. However, for low frequencies, the Nyquist plot became erratic except at the previously mentioned frequency peaks of the noise. However, the envelope of the Nyquist plot could be easily identified from the data and is represented by the dashed line. In both cases, the imaginary portion of the impedance rolled off below about 20 *Hz*; however, the amount of roll off significantly varied between the two cells.

Comparative Example

Another type of lead-acid battery cell was tested in the laboratory using a controlled source of white-noise. The only loads on the battery were a fixed resistor across which the current was measured and an electronically controlled resistor providing the white noise. The resulting Nyquist plot was much smoother than that of FIG. 3 and had different values of impedance. However, it showed similar behavior at high frequencies and a roll off below 20 *Hz*. It additionally showed a sharp rise in the imaginary impedance below about 1 *Hz*.

In two of the simpler models of Hampson *et al.*, the roll off is caused by a conductive path in parallel with the charging plates of the battery while the high-frequency rise is associated with an impedance placed in series with the plates.

The measuring circuit of the inventive example suppressed the response below 3 *Hz*. It would be desirable to modify the circuitry of FIG. 2 to provide fixed DC offsets of the input signals, thus allowing DC coupling to the analyzer which would be more accurate at low frequencies.

The lowest measurement frequency is determined by the duration of the measurement. A recording time of tens of minutes will give impedance information with a lower frequency limit of several millihertz. The highest frequency is determined by the signal measurement rate. Modern Fourier-transform instrumentation has a measurement bandwidth covering the range from below a millihertz to tens of kilohertz. This frequency range also contains the most meaningful information about battery impedance.

Relying on the noise generated by the system as the test signal causes the problem that the test signal is not perfectly random. Instead, it contains some fairly narrow peaks. However, the spectral content of the noise appears rich enough to provide sufficient information in the required frequency regions, particularly if long time records are digitally acquired at high time resolution. Such records can be tens to hundreds of megabytes in length. With appropriate preprocessing, commercial instrumentation can handle such data. For high frequencies, smaller records of several kilobytes can be taken from the long single record with substantial overlap of the smaller records. Calculations for each smaller record can be averaged after the Fourier transform. This technique also reduces the windowing effect inherent in Fourier transforming such records. For low frequencies, where high time resolution is less important, down sampling will reduce the record size and resultant transform time.

Although the above embodiment used a commercial impedance analyzer to measure complex impedances, other means are available including analog equipment, such as a phase-sensitive detector and tunable filter, and digital

processing equipment, such as a high-speed digitizer and a computer. Although the above embodiment connected both the operating electrical switch and the rectifier across the battery, the invention will work with any equipment impressing a spectrally rich signal on the DC power bus.

The invention thus allows *in situ* testing of batteries with no need to disconnect the battery from the circuit it is backing up. Furthermore, the test is relatively quick and does not require discharging the battery.

What is claimed is:

1. A battery tester for testing a string of a plurality of serially connected batteries connected to a power input terminal of operating electrical equipment, comprising:

an impedance measuring device; and

at least three electrodes connected to said impedance measuring device and removably connected to said string of serially connected batteries without disconnecting said string of batteries from said power input terminal so as to measure a voltage across any selected one of said batteries and a current through said string of said batteries.

2. A battery tester as recited in Claim 1, wherein said impedance measuring device determines an impedance of said selected one battery at a plurality of frequencies, said impedance being complex.

3. A battery tester as recited in Claim 2, wherein said impedance measuring device comprises:

first means for measuring a voltage across said selected one battery at a plurality of sampling times while said equipment is operating;

second means for measuring a current through said selected one battery at said plurality of sampling times; and

means for obtaining a impedance at a plurality of frequencies from said measured current and voltage.

4. A battery tester as recited in Claim 3, wherein said obtaining means includes means for Fourier transforming to obtain said impedance at said plurality of frequencies.

5. A battery tester as recited in Claim 3, wherein said second means comprises a link electrically connecting said battery with a second battery and a voltage probe connected across said link.

6. A battery tester, comprising:

a DC bus;

a source of DC voltage powered by an AC power line and powering said DC bus;

electrical equipment connected to and powered by said DC bus;

a plurality of batteries, each having a pair of terminals;

a plurality of conductive links interconnecting said batteries and said DC bus through said terminals such that said plurality of batteries are serially

connected to said DC bus;

an impedance meter connected across terminals of one of said batteries and across one of said links and measuring a complex impedance of said one battery, at least one of said source of DC voltage and said electrical equipment providing a test signal for said impedance meter.

7. A battery tester as recited in Claim 6, wherein said impedance meter measures said complex impedance at a plurality of frequencies in a frequency range between 0.001 *Hz* and 100 *kHz*.

8. A battery tester as recited in Claim 7, wherein said plurality of frequencies comprises a plurality of frequencies below a principle line frequency of said AC power line.

9. A method of testing a battery connected to operating electrical equipment, comprising the steps of:

serially connecting a string of batteries to a DC power terminal of an electrical equipment;

measuring a current and a voltage impressed on a selectable one of said batteries by said electrical equipment; and

determining a plurality of frequency components of complex impedance from said frequency components of said current and voltage.

10. A method as recited in Claim 9, wherein said DC power terminal comprises a power supply input.

11. A method as recited in Claim 9, further comprising associating characteristics of said complex impedance with components of an equivalent circuit of said battery.

12. A battery tester as recited in Claim 1, wherein said string of batteries includes conductive links electrically connecting said batteries in series to said operating electrical equipment and wherein two of said electrodes are connectable across one of said links and are connected to a current-measuring input of said impedance measuring device.

13. A battery tester as recited in Claim 6, wherein said impedance meter is removably connected to said one battery.

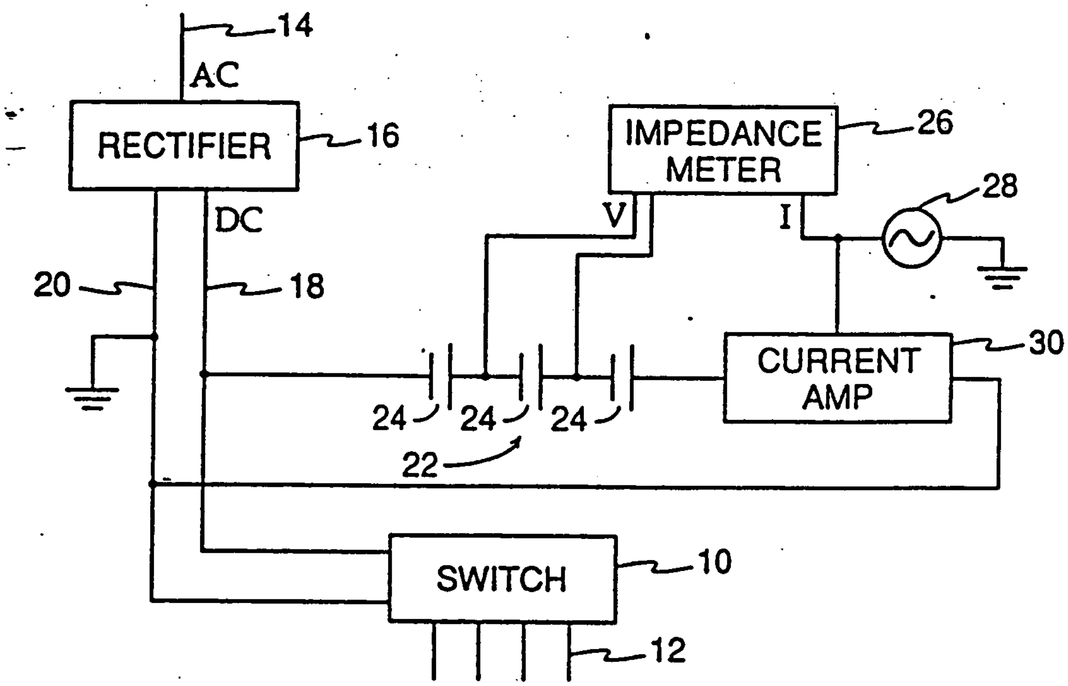


FIG. 1
(PRIOR ART)

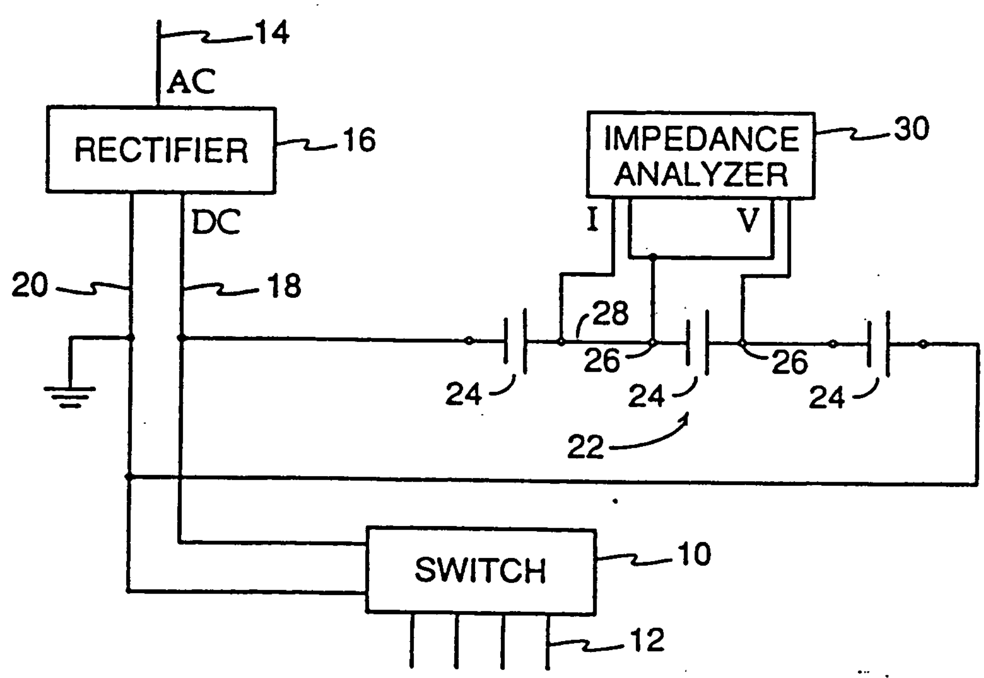


FIG. 2

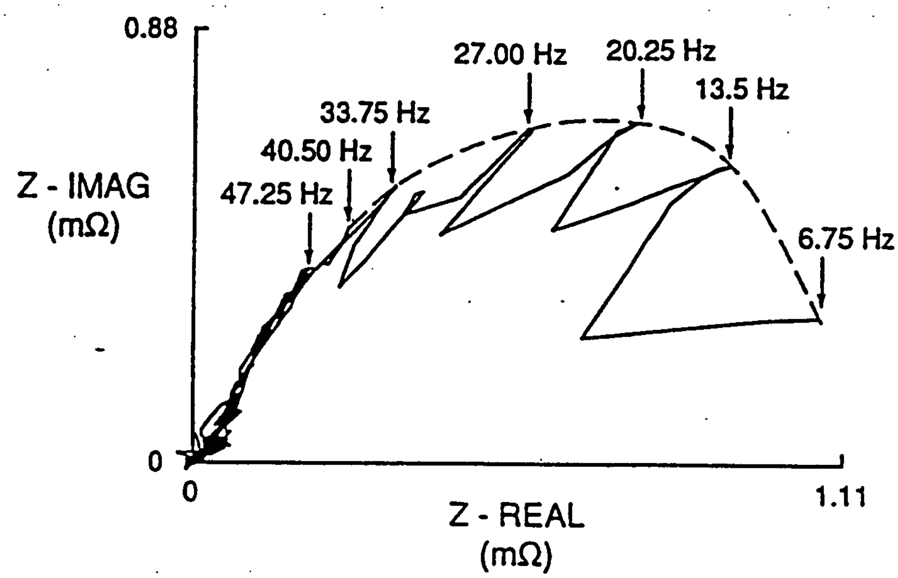

0.88
Z - IMAG
(mΩ)
0
0
1.11
Z - REAL
(mΩ)
27.00 Hz
20.25 Hz
13.5 Hz
33.75 Hz
40.50 Hz
47.25 Hz
6.75 Hz

FIG. 3

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INTERNATIONAL SEARCH REPORT

PCT/US93/02628

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :G01N 27/416
US CL :324/427,430,434; 320/48; 340/636
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 324/426,429

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A, 3,942,104 (BYRNE) 02 MARCH 1976	1-13
A	US,A, 4,678,998 (MURAMATSU) 07 JULY 1987	1-13
A	US,A, 4,490,944 (STEELE ET AL) 10 JULY 1990	1-13
A	US,A, 5,099,211 (NOWAK) 24 MARCH 1992	1-13
A,P	US,A, 5,175,531 (WHITMIRE ET AL) 29 DECEMBER 1992	1-13

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
17 MAY 1993	29 JUN 1993

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